Defense Technical Information Center Compilation Part Notice

ADP023936

TITLE: Characterization of Sea Fighter, FSF-1, Wave Slam Events

DISTRIBUTION: Approved for public release; distribution is unlimited.

This paper is part of the following report:

TITLE: International Conference on Numerical Ship Hydrodynamics [9th] held in Ann Arbor, Michigan, on August 5-8, 2007

To order the complete compilation report, use: ADA495720

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, etc. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP023882 thru ADP023941

Characterization of *Sea Fighter*, FSF-1, Wave Slam Events

T.C. Fu, A.M. Fullerton, L.M. Minnick
(Naval Surface Warfare Center, Carderock Division)

ABSTRACT

The development of computational tools used for high-speed sealift, HSSL, ships requires specific data for validation. These HSSL design tools specifically address the vessel's performance and loading, including the ships behavior during wave slam events. Because very little, if any, full-scale data of this type exists, the primary objective of this work was to obtain full-scale qualitative and quantitative wave slamming data of the *Sea Fighter (FSF-1),* a high-speed multihull vessel developed by the Office of Naval Research. This data included measurement of the ambient environmental conditions, the incident waves impacting the ship, ship motions, and visual documentation of the free-surface/wave field surrounding the ship during slamming events. The rough water trial took place April 18-21, 2006 and several wave slams were documented. This paper will describe four of the typical wave slam events, which occurred during the field test.

INTRODUCTION

A specific need exists for a high-speed sealift (HSSL) capability that will allow forces to deploy rapidly from CONUS (Continental United States) to foreign ports. These HSSL vessels are projected to carry a payload of between 3500 and 4000 tons and operate at sustained speeds on the order of 43 knots or more, with a range of at least 5000 nautical miles. Adding to the technical challenge posed by this speed and endurance requirement is the fact that foreign ports are likely to be relatively small and undeveloped, requiring that the ships be relatively short and of relatively shallow draft. Together these requirements suggest that the resulting ships would need to be unconventional multihull vessels. The development of design tools and the accompanying test instrumentation for high-speed ships is of major impact to the Navy. The ability to understand, predict, and simulate the true behavior of full-scale high-speed Navy ships is dependent upon acquiring full-scale data for both physical understanding and validation of predictive tools.

The development of computational tools used for HSSL ships requires specific data for validation. Deterministic models of the sea surface in time and space are growing in their maturity and complexity, as are vessel motion prediction codes. However, little full-scale field data exists for ships of this type traveling at high speeds. Therefore the primary objective of this trial was to obtain full-scale qualitative and quantitative wave slamming data. This data included measurements of the ambient environmental conditions (wind and waves), the incident waves impacting the vessel, ship motions, including accelerations and angular rates, and visual documentation of the free-surface/wave field surrounding the ship. Associated with these measurement objectives were accompanying instrumentation development objectives to ensure the primary objectives could be met. Critical to improving the prediction of motion dynamics and vessel loading of full-scale vessels, is an ability to measure the ambient surface wave field in and around an underway vessel. An increasing knowledge gap exists in the ability to accurately measure the surface wave field from an underway vessel for analysis of hull motions and structural response. The ability to meet these instrumentation objectives was also explored throughout the trial.

During the rough water trial from April 18-21, 2006 several underway wave measurement systems were deployed from *Sea Fighter (FSF-1)* to allow the measurement of the surface wave field. The Naval Surface Warfare Center Carderock Division, Code 5600 employed an array of ultrasonic wave height sensors to measure the free-surface elevation close to the ship. Additionally, inertial and GPS motion sensors were used for the evaluation of slamming loads measured onboard the *Sea Fighter* under a range of vessel speeds and sea states. The data will be used to validate existing numerical codes and to identify gaps of understanding, which require further research.

ROUGH WATER TRIAL

The *Sea Fighter*, FSF-1, see Figure 1, is a high-speed experimental vessel, developed by the Office of Naval Research (ONR). Christened in 2005, she is an aluminum catamaran (specific details of the ship design are listed in Table 1) with both diesel engines (two 5500 HP each) and gas turbines (two rated at 34 kHP). Four steerable Kamewa water jets propel the *Sea Fighter* at 20 knots utilizing diesel engines and greater than 50 knots, in calm water, using her gas turbines. Additionally, the ship has an installed "science package" of strain gauges, accelerometers, pressure gauges, and underwater viewing windows.

Figure 1: Images of the *Sea Fighter*, FSF-1, underway.

Table 1: *Sea Fighter*, FSF-1, specifications.

Length (Overall)	79.9 m (262 ft)
Length (Waterline)	73 m (240 ft)
Beam	22 m (72 ft)
Draft	3.5 m (11.5 ft)
Displacement	960 Metric Tons
Max Speed	50+ knots
Max Speed (SS4)	40+ knots
Max Speed (Diesels only)	20+ knots
Range	> 4000 NM @20 knts

In the winter and spring of 2006, the *Sea Fighter* underwent rough water trials to assess its operational profile in high sea states (SS4 and SS5). The second of these rough water trials took place 18-20 April 2006 as the ship transited from Esquimalt, British Columbia, Canada to San Diego, CA. Figure 2 shows the course of the transit. Note the partial octagon just south of the Oregon/California border, this maneuver allowed for the ship to be tested at a range of wave headings. Table 2 shows the significant wave height and period as well as wave heading for the test period. This data was obtained from the onboard TSK sensor, a deployed Neptune wave buoy, and from NOAA buoys. Ship speed was 40 knots for the first day and dropped to 20 knots for the rest of the cruise.

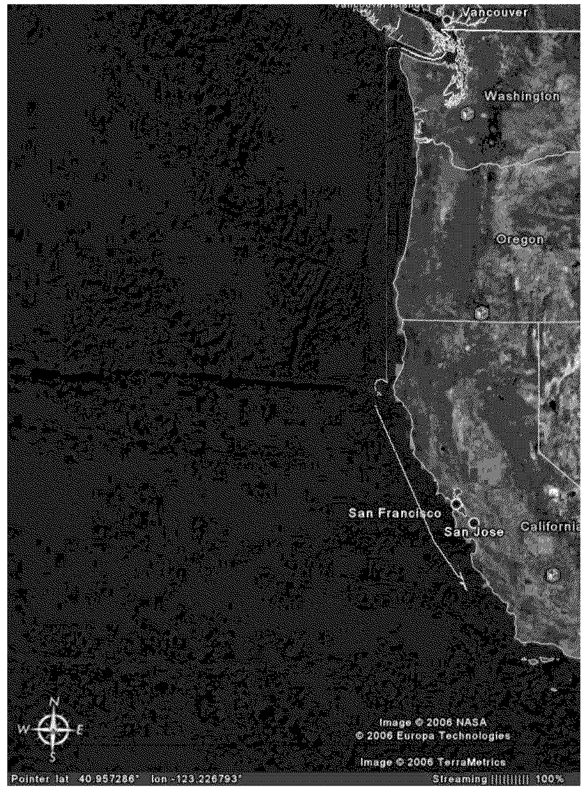


Figure 2: *Sea Fighter*, FSF-1, rough water trail course.

Table 2: Wave data from rough water trial.

Date	Time GMT	Hs m	To sec	Ts sec	Dir deg - M	Sensor
4/19/06	300	2.6	10	-	WSW	46087*
4/19/06	427	2.5	9.1	7.7	WSW	46087
4/19/06	455	2.4	8.3	-	WSW	46087
4/19/06	1500	1.5	11	6	NNW	Neptune Buoy
4/19/06	1915	2	6.8	-	-	Onboard TSK
4/19/06	2155	1.9	9.1	-	-	Onboard TSK
4/20/06	130	1.9	9.1	7.4	-	Onboard TSK
4/20/06	1500	2.3	7.1	-	332	46028**
4/20/06	1600	2.3	6.7	-	324	46028
4/20/06	1627	2	7.4	-	321	Neptune Buoy
4/20/06	1655	2.1	6.9	-	6	Neptune Buoy
4/20/06	1825	2.6	5.9	16.4	-	Onboard TSK
4/20/06	2300	2.3	16.1	7.1	308	46028
4/20/06	2320	2.7	6.3	16.4	-	Onboard TSK

FIELD EXPERIMENT DESCRIPTION

Ship Motions

A combined GPS and inertial motion package as well as three Litton LN200s were on board to record ships motions. Ship motion data was collected continuously throughout the trial.

LN 200

Three Litton LN200s were installed aboard the *Sea Fighter*. Each LN200 is an inertial measurement unit consisting of three fiber optic gyros and three linear accelerometers. Table 3 provides a complete list of the data collected by these packages. An LN200 was mounted in the bow of each hull (port and starboard) along the hull's centerline and the third package was mounted in the Mission Bay starboard of the vessel centerline as shown in Figure 3. This allowed for the motion of each hull and the overall ship to be examined and compared. The three LN200 inertial motion units provided linear and angular accelerations, angular rates, roll, pitch, and heading data all taken at a sampling rate of 200 Hz.

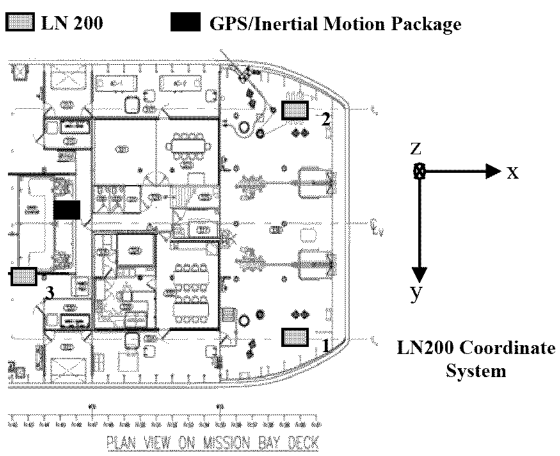


Figure 3: Diagram showing the locations of the deployed motion packages on the ship.

3DM-GX1 and SUPERSTAR II GPS

A combined GPS/motion package was installed near the vessel centerline and slightly aft of the second forward most watertight bulkhead as shown in Figure 3. The motion package consisted of a gyro enhanced orientation sensor (3DM-GX1), a SUPERSTAR II GPS, and a Persistor CF2 CPU. The 3DM-GX1 sensor consists of three angular rate gyros, three orthogonal DC accelerometers, three orthogonal magnetometers, and a multiplexer. The gyros track dynamic orientation while the accelerometers and magnetometers track static orientation. The 3DM-GX1 combines the static and dynamic responses in real time and records 20 samples per second. The SUPERSTAR II GPS provides position, velocity, and time data once every second. The CF2 runs on battery power and combines and stores the collected data on a flash disk. A complete list of the data recorded by this package is provided in Table 3.

Table 3: Summary of data collected by LN200 and GPS/Inertial motion package.

	LN200	GPS/Inertial Package
Heading	√	
Pitch	√	√
Roll	√	√
Yaw	√	√
X Linear Acceleration	√	√
Y Linear Acceleration	√	√
Z Linear Acceleration	√	√
X Angular Acceleration	√	
Y Angular Acceleration	√	
Z Angular Acceleration	√	
X Angular Rate	√	√
Y Angular Rate	√	√
Z Angular Rate	√	√
Latitude		√
Longitude		√
Altitude		√
Ground Speed		√
Track Angle		√
N. Velocity		√
E. Velocity		√
V Velocity		√
Date		√
Time		√

Wave Field Characterization

To provide suitable validation data for full-scale wave slamming, the incoming wave must be characterized. An array of thirteen acoustic sensors provided point measurements of the near-field free surface. Nine standard video cameras were used for qualitative observations and were mounted in the same general locations as the acoustic sensors.

Senix Ultrasonic Waveheight Sensors

Thirteen Senix ToughSonic distance sensors were used to measure the elevation of the free-surface at various locations around the vessel. An ultrasonic wave height transducer emits and receives the reflection of an acoustic signal. The time between the emission and receipt of the pulse allows for the calculation of the distance between the probe and the free-surface of the water. The probes have a 15 degree spread angle, meaning they average the signal received from a rather large patch of water, depending on the distance to the water surface itself. The sensors onboard the *Sea Fighter* were mounted approximately 4.5-6 m from the water surface. The sensors have a 10 Hz sampling rate, a range of 0.25 m to 9 m, with an accuracy of 1.25 mm. Figure 4 shows the location of the underway cameras and ultrasonic sensors, which were collocated at each of seven locations around the bow of the vessel. Table 4 lists the longitudinal and transverse locations of the bow sensors relative to forward most bulkhead and vessel centerline. Sensors 3, 4, 6, and 7 and their associated cameras were mounted in the forward anchor wells as shown, while the remaining sensors were mounted off booms from the forecastle deck. Four additional sensors were deployed around the stern (two at the front of the boat ramp in the tunnel and two at the aft end). Data from the sensors and cameras was collected the entire time the ship was at sea.

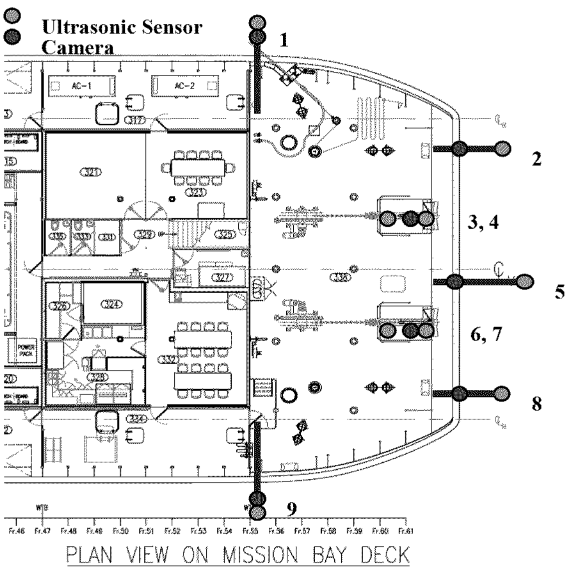


Figure 4: Diagram of the location of the bow ultrasonic and camera locations.

Table 4: Locations of the bow ultrasonic sensors.

Ultrasonic Senors		Longitudinal* Distance (m)		Transverse Distance (m)	
Port	**1**	1.04	Fwd BHD	11.5	Port CL
Port Bowline	**2**	0.62	Fwd BHD	5.89	Port CL
Port Fwd Anchor	**3**	0.71	Fwd BHD	2.19	Port CL
Port Aft Anchor	**4**	2.38	Fwd BHD	2.19	Port CL
Center	**5**	1.17	Fwd BHD	0.52	Stbd CL
Stbd Fwd Anchor	**6**	0.76	Fwd BHD	2.19	Stbd CL
Stbd Aft Anchor	**7**	2.42	Fwd BHD	2.19	Stbd CL
Stbd Bowline	**8**	0.93	Fwd BHD	5.92	Stbd CL
Stbd	**9**	4.21	Fwd BHD	11.57	Stbd CL

* referenced BHD is BHD at frame 55

Underway Cameras

An array of nine cameras was deployed to provide qualitative support to the wave measurements. Seven cameras were mounted around the bow of the ship and two more cameras were deployed at the stern (from each hull, looking aft). The cameras were standard color video cameras in waterproof housing operating at 30 frames per second. Figure 4 shows the locations of the bow cameras.

DATA PROCESSING

The overall test plan objective was to measure the wave elevation and ship motions while undergoing high speed slamming events. Data was collected continuously throughout the four-day trial. Four slam events were identified and analyzed and are listed in Table 5. A slam event was determined by the encounter of a wave that was large enough to make impact with the wet deck (refer to yellow arrow in Figure 5). Three of the events occurred on the same day while cruising at speeds in the range of 15 to 20 knots, while the fourth event occurred the day before while traveling at a higher speed of 30 knots. For each event the wave field was characterized using the ultrasonic sensors and ship motions were analyzed.

Table 2 summarizes the sea state data collected by three independent instruments; a TSK

Shipborn Wave Height Meter, a Neptune buoy, and a NOAA buoy. The rows highlighted in yellow provide sea state data for the slam events listed in Table 5 The wave heights seen by all four events were between 2.3 and 2.7 m. Approximately 6 second wave periods were seen in the 20th while 10 second periods were seen on the 19th.

Table 5: Summary of Slam Events.

Slam Event	Date	Time (GMT)	Speed (knt)
1	19-Apr-06	2:33	30
2	20-Apr-06	19:30	19.8
3	20-Apr-06	21:36	16.4
4	20-Apr-06	22:08	15.8

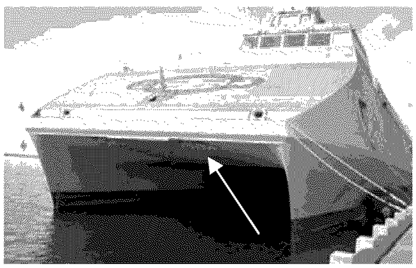


Figure 5: Schematic showing the bottom of the hull that required impact for a slam event.

Wave Field Characterization

The data collected by the ultrasonic sensors was used to characterize the wave field seen by the ship before, during, and after each slam event. Due to the rough test environment, during slam events the data collected by the ultrasonic sensors had more signal losses than typically seen when using the instruments for experiments in the tow basin. Therefore, the raw data first needed to be filtered and the losses corrected. Signal losses were identified based on the slope between adjacent points. If the absolute value of the slope between two points was greater than a given threshold, 3 m/sec, then those data points were flagged as part of a signal loss. The threshold was chosen based on the sea state information and instrument capabilities. Data from the ultrasonics was collected at 10 Hz, therefore, in sea state 4 conditions it is highly unlikely that a wave steepness of that magnitude could be achieved in only 0.1 seconds; that would require the wave height to change by 3 m in only 0.1 seconds.

Once a data point was flagged as part of a signal dropout its value was reset to zero. The dropouts, now zero values, were then filled in by linearly interpolating between the two nearest non-zero values (the last recorded value before the loss and the first point once reconnected). Figure 6 shows an example of the raw data (with dropouts) and the corrected data for the port bowline sensor for Slam Event 2. The dropouts in the raw data can be recognized as the steep vertical blue lines. The gap in the data shortly after 19:29 GMT, denoted by the flat red line, is different than an ultrasonic dropout. It is caused by a loss of the time feed into the data acquisition program and is a loss of data that cannot be replaced; therefore these gaps remain in the data sets while dropouts are corrected. It was impossible to guarantee that every dropout was eliminated; however, the majority of dropouts were identified and corrected, producing a more complete set of data to use in analysis.

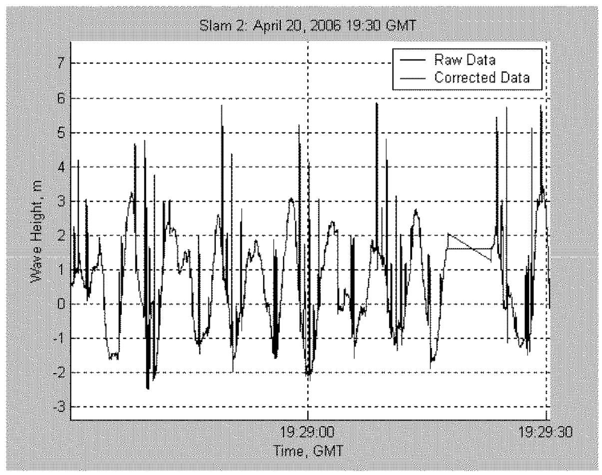


Figure 6: Example of raw and corrected ultrasonic data.

In addition to correcting the data for signal losses the data also had to be corrected for ship motions. Motion data from LN200 package 3 was used since it was located closest to the ship CG. Given the distance of the instrument from the vessel CG the height in the ultrasonic readings due to ship motions was determined using equations 1 and 2. This height, z_{pitch} and z_{roll}, was then removed from the ultrasonic readings. The derivation of these equations is illustrated in Figure 7.

$$z_{pitch} = d_{cg} \cdot \sin\theta \quad (1)$$

$$z_{roll} = d_{cg} \cdot \sin\phi \quad (2)$$

Where:

d_{cg} = longitudinal or transverse distance to ship CG

θ = pitch angle from LN200 3

ϕ = roll angle from LN200 3

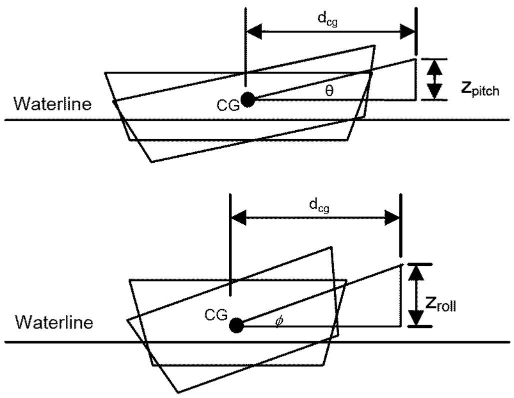


Figure 7: Diagram illustrating derivation of Equations 1 and 2.

Once the raw data was corrected the wave field was able to be determined. Figure 8 shows a portion of the corrected data for all the bow ultrasonics for Slam Event 2. In total, there were nine bow ultrasonics, (refer to Figure 4 and Table 4 for details of the ultrasonic locations) however, the starboard aft anchor sonic is not included in the data set because it was damaged earlier in the test. The purple trend line is data collected by the center ultrasonic and Figure 8 shows that it still has a significant number of dropouts even after the data was processed to help eliminate the dropouts created by a signal loss. The center ultrasonic, as well as the port and starboard ultrasonics, was mounted on a boom that projected out from the front of the ship. This mounting configuration allowed the ultrasonics acoustic beam to not be obstructed by any part of the ship. While in rough seas, especially during a slam event, the boom itself had its own motion making it difficult to keep a continuous data signal. It is assumed that the increase in the number of dropouts seen by these ultrasonics is due to the motion of the booms.

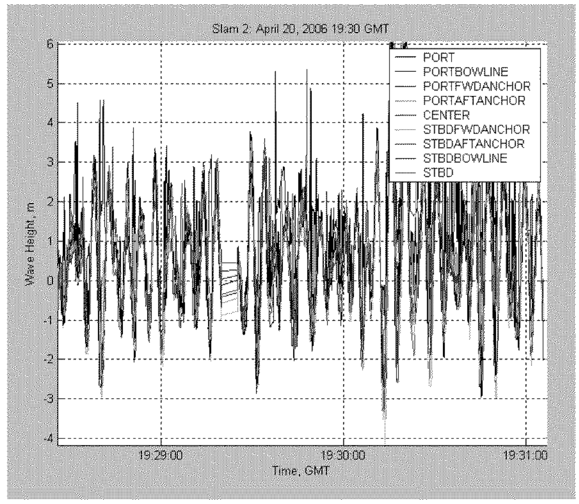


Figure 8: Plot of bow ultrasonics for Slam Event 2.

Once the port, starboard, and center ultrasonics were omitted from the analysis the four sensors mounted in the anchor wells were compared to one another to determine an average overall anchor well wave profile and the same analysis was applied to the port and starboard bowline sensors. Figure 9 shows the comparison of the port and starboard bowline sensors. The blue and red trend lines represent the corrected data for the port and starboard bowline sensors respectively. The figure shows that the data collected by both sensors was similar, and therefore, an average between the two was calculated and used in determining the overall wave field during this event.

The same approach was used in analyzing the data from the anchor well sensors. Figure 10 shows the data from the three functioning anchor well ultrasonics. All three ultrasonics show similar wave fields, however, the port forward anchor ultrasonic still has various dropouts after the slam event that were unable to be corrected. Therefore, this ultrasonic was omitted and the port aft and starboard forward ultrasonics were averaged to determine the average anchor well wave profile. The anchor well average and bowline average were then averaged to determine the overall wave field seen by the vessel before, during, and after the slam event. Figure 11 shows the anchor well and bowline averages and the final average for Slam Event 2, which is an average of the anchor well and bowline averages.

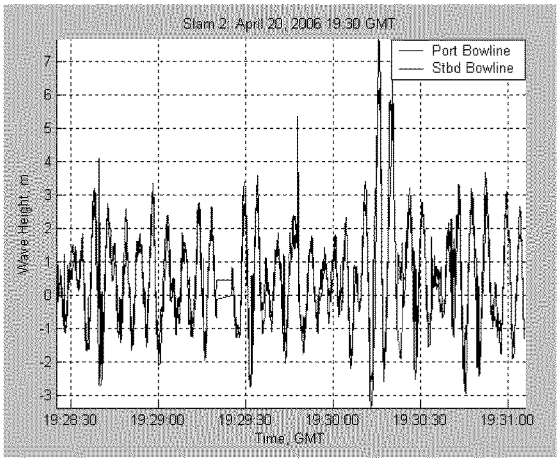


Figure 9: Comparison of port and starboard bowline ultrasonics for Slam Event 2.

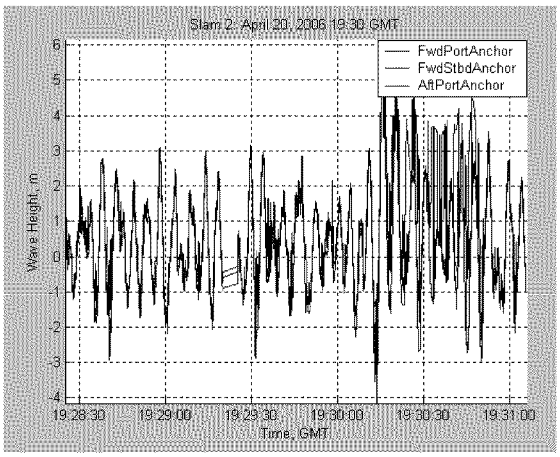


Figure 10: Comparison of Anchor Well ultrasonics for Slam Event 2.

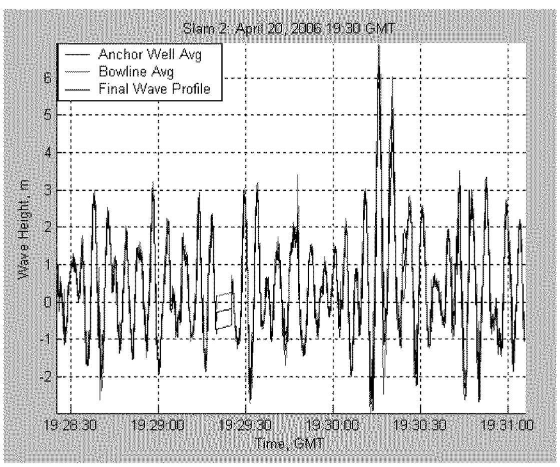


Figure 11: Comparison of Anchor Well average, Bowline average, and Final Wave Height Profile for Slam Event 2.

This approach of comparing sensors to one another and determining an average profile for a given bow location was then used in determining the overall average wave field for each slam event.

Ship Motions

Ship motions were measured using two separate motion packages: a set of three Litton LN200s and a combination GPS and inertial motion package. Figure 12 shows a comparison between the three LN200s and the motion package for ship pitch during Slam Event 4. All four instruments show the same trend in the data. The data from LN200 1 and LN200 2 practically lie on top of one another and only have a small phase shift from LN200 3, which has a short lag time behind the motion package. This small variation in signal is due to the location of the instruments onboard *Sea Fighter* (refer to Figure 3). LN200 1 and 2 were both roughly the same distance forward of the center of gravity and equal distances longitudinally off the vessel centerline, making the data collected by each very similar as expected. LN200 3 and the motion package were located aft of LN200 1 and 2, closer to the vessel CG; and this is reflected in their data. It is important to note that there is limited control in a full-scale *in-situ* experiment. Therefore, it is also likely that there is some roll contamination in the pitch readings and vice versa due to an inability to mount the instruments completely level which may also be a contributing factor in the variations seen in the ship motion instruments. This comparison of the motion packages was used to further validate the data collected by each instrument showing that each was functioning properly during the trial.

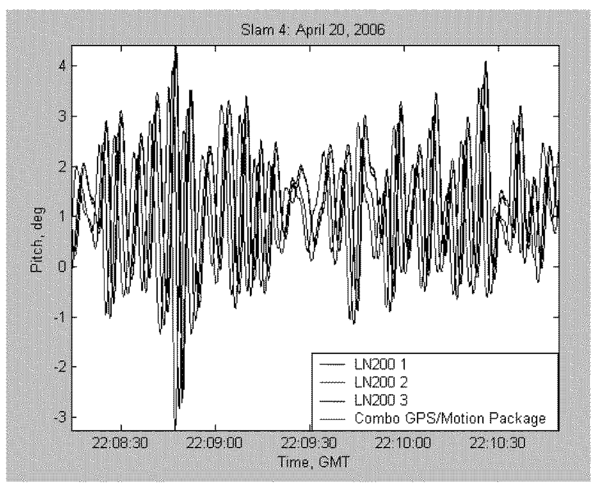


Figure 12: Pitch comparison between ship motion packages.

Some conclusions can be drawn from the comparison among the LN200s. The instruments were specifically chosen to be placed one in each of the side hulls and one near the centerline of the vessel to examine ship bending during high impacts events. The consistency throughout the slam event of the data in Figure 12 shows that no significant bending has occurred. However, due to the possibility of roll contamination and without additional instruments such as strain gages mounted in each hull, it is difficult to completely eliminate the possibility of some bending due to a slam event. Additional structural data and analysis for *Sea Fighter* will be reported by NSWCCD, Code 60.

RESULTS

To completely characterize a slam event it was necessary to look at the ship motions, wave field data, and the video from the underway cameras together and draw conclusions. Specifically slam events at the bow were analyzed, therefore LN200 1 was used for the analysis of the ship motions because it was located closest to the bow of the ship (LN200 2 could have been used as well since the only difference between its location and the location of LN200 1 is that it was mounted port of the vessel centerline). Each slam can be identified by a large wave that has a significant impact on the ship's motions. A significant impact is defined as motions that are outside of an average envelope of motions seen for a given time period.

Slam Event 1

Figure 13 provides wave height, pitch, vertical linear acceleration, and speed plots for Slam Event 1. The slam can be recognized by the spike in the vertical acceleration plot. It is important to note that the y-axis in the z linear acceleration plot is actually a measure of the change in z linear acceleration in g-force. Therefore, 0 g's is the standard acceleration due to gravity, and any value below or above it corresponds to additional acceleration of the ship. For example, when the graph spikes to close to 1 g, as in Figure 13, then the ship is experiencing 1 g of vertical acceleration in addition to its vertical acceleration due to gravity.

Figure 13 shows that the pitch of the ship varies from approximately 0 to 2 degrees and linear acceleration varies from ±0.2 g's. The wave heights start in a -2 to 0 m envelope and then shift to a ±2 m envelope. The slam occurs shortly after 2:33:30 GMT and can be identified on the graph by the sharp spike in z linear acceleration. It involves three consecutive increasing crests, all above the bounds of the 2 m envelope. The first two crests cause a slam with the second crest producing the most violent slam, as seen by the large spike in vertical acceleration. In addition, during the trough before the second crest the bow of the ship rises out of the water and is suspended in the air just before the second crest slams into the bow. With the second crest the bow pitches down to the minimum pitch angle for this time period, -2 degrees, then quickly pitches up to 4 degrees (the maximum) and pitches down again to 1 degree with the final crest.

Figure 14 shows this sequence of events using the onboard bow center and starboard cameras respectively. The first row of snapshots show the first crest which causes a small slam, but it is not large enough for white water to be seen by the center camera. The second row of photos shows the first trough that lifts the bow out of the water just before the second slam. The third row shows the second crest slamming into the bow, which is the most violent slam of the three crests. The intensity of the slam can be seen by the large amount of whitewater in the bow camera view in both the third and fourth row photos. The fourth row shows the following trough and the remnants of the previous slam can still be seen by the white water and spray that is still present in the bow center camera. The last row shows the last crest, which is the largest crest in the wave height plot, but it does not produce a slam.

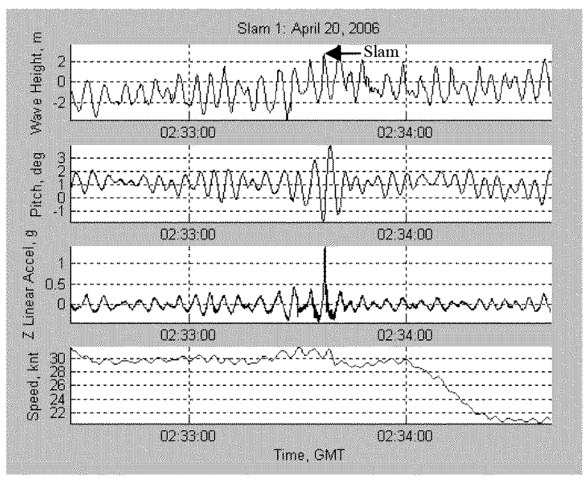


Figure 13: Slam Event 1: Wave Height, Pitch, and Vertical Acceleration plots.

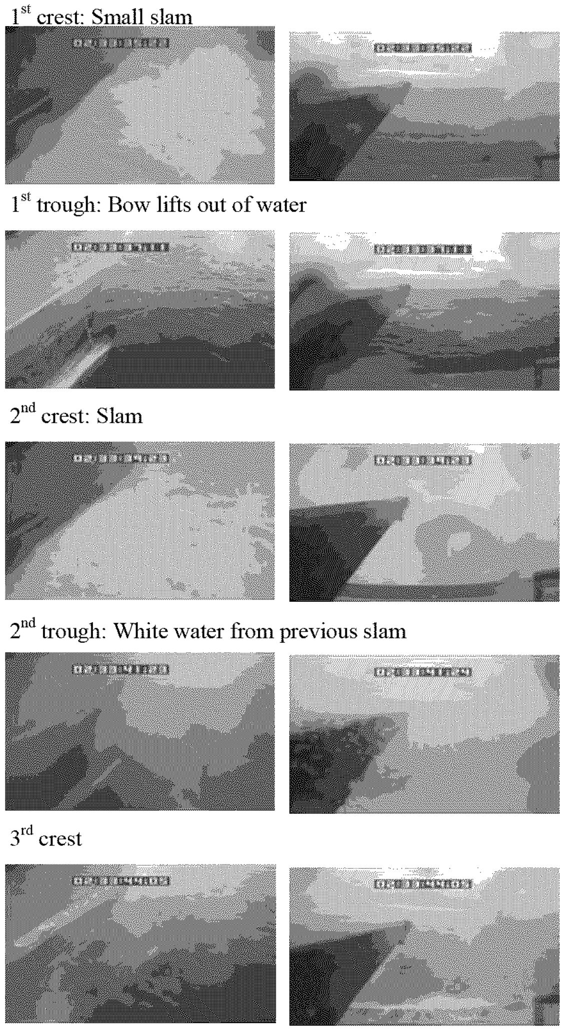


Figure 14: Slam Event 1: Snapshots of on-board cameras.

Slam Event 2

Figure 15 provides plots of the wave height, pitch, z linear acceleration, and speed data for Slam Event 2. The spikes in all three graphs at approximately 19:30:15 GMT indicate the actual slam event. For this given time period the wave heights stay roughly within a ±2 m range except during the slam when the wave crests double in size. Similarly, pitch stays steady in a range of 0 to 2 degrees and then increases to a range of -2 to 4 degrees during the slam. Finally, the z linear acceleration fluctuates between ±0.2 g's and spikes to ±0.4 g's during the slam.

The event begins with a 2 m wave trough, which is followed by a 6 m crest, a trough of about 1 m and another large 5 m crest. Both troughs cause the bow of the vessel to lift out of the water and both crests cause a slam impact with the bow. Figure 16 provides snapshots from three of the onboard cameras (starboard, center, starboard bowline respectively) showing the sequence of events of the slam as described. The first row of snapshots shows the ship encountering the first trough when the bow lifts completely out of the water. Row 2 shows the impact of the first crest and the small slam it causes. The third row shows the second trough and the bow again lifting out of the water. Finally, the fourth row of snapshots shows the larger slam caused by the impact of the second crest.

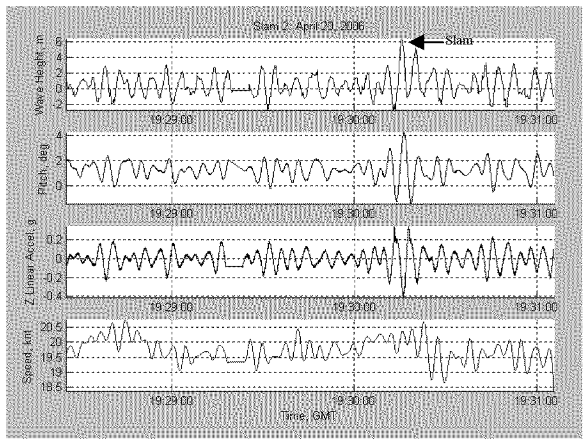


Figure 15: Slam Event 2: Wave Height, Pitch, and Vertical Acceleration plots.

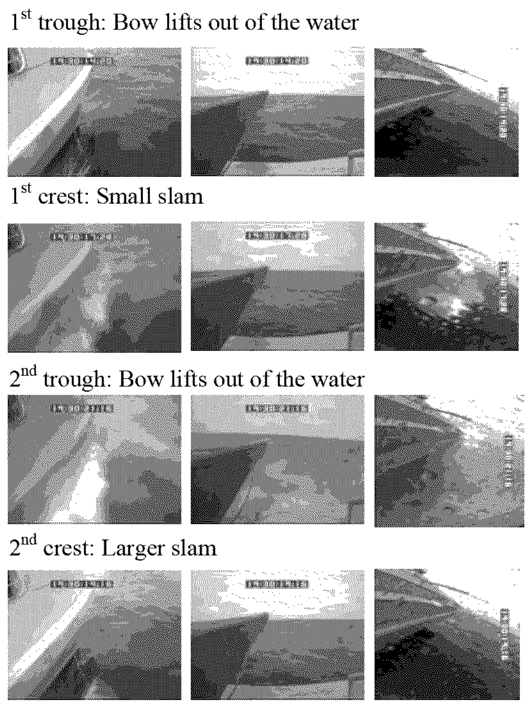


Figure 16: Slam Event 2: Snapshots from onboard cameras.

Slam Event 3

Figure 17 provides wave height, pitch, z linear acceleration, and speed plots for Slam Event 3. There are three separate slam events in the time span shown in the figure. There is one shortly after 21:38:00 GMT, labeled A on the graph and denoted by the largest spike in z linear acceleration seen. Slam B occurs at approximately 21:38:45 GMT and Slam C occurs towards the end of the plot near 21:39:30 GMT. On average the wave heights stay within an envelope of ±3 m. When the wave heights are greater than ±3 m then it is likely a slam occurs. Similarly, pitch stays within a range of 0 to 3 degrees except during a slam where it oscillates from -2 to 4 degrees. In addition, the ship experiences a steady vertical acceleration of ±0.2 g except for during a slam.

The most significant slam is Slam, A which occurs at approximately 21:38:00 GMT. It begins with a large crest of 4 m followed by a 2 m trough and then a larger crest of over 6 m followed by another 2 m trough. The slam occurs as the ship encounters the second and larger crest, which can be seen by the large spike in vertical acceleration up to 0.5 g. Figure Figure 18 shows snapshots of three of the onboard cameras during the slam event; the starboard, center, and starboard bowline cameras respectively. The first row in Figure 18 shows the first (4 m) crest and the second row shows how the bow of the ship comes completely out of the water as it encounters the first 2 m trough. Next, as seen in the third row and fourth rows, the 6 m crest slams into the bow causing the large spike in vertical acceleration. The second 2 m trough (fifth row) causes the bow to rise out of the water again; however the next crest is not large enough as seen by the sixth row of snapshots to cause additional slamming.

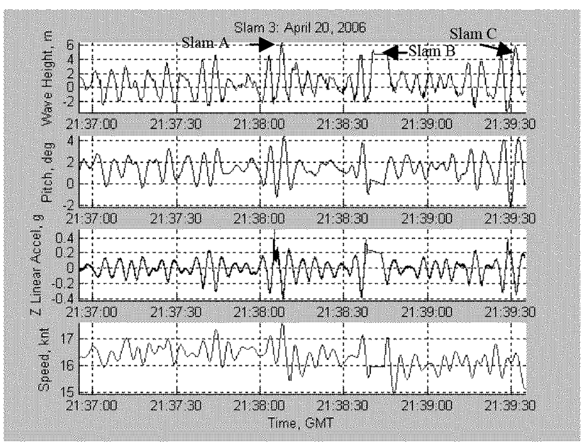


Figure 17: Slam Event 3: Wave Height, Pitch, Vertical Acceleration plots.

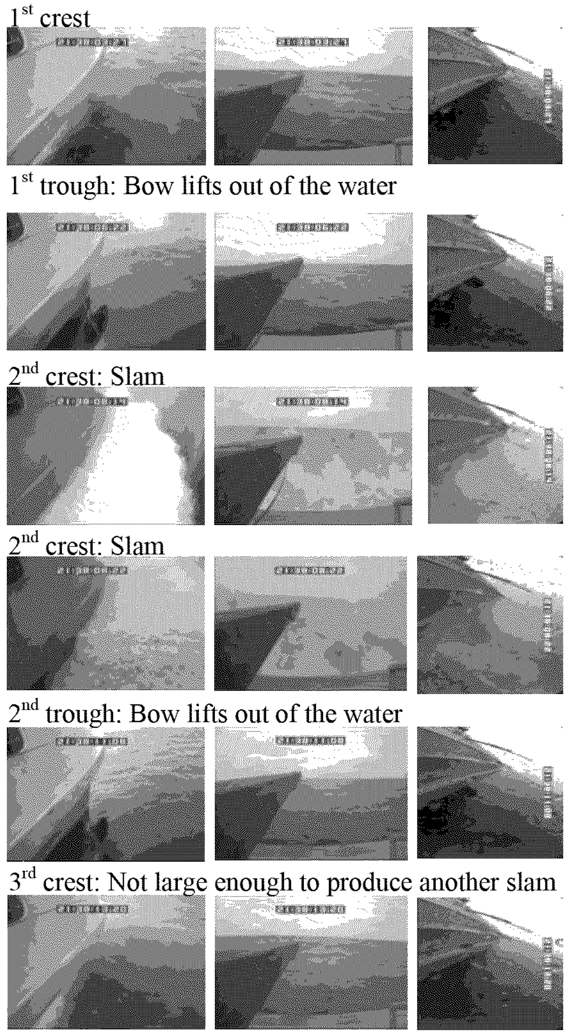


Figure 18: Slam Event 3A: Snapshots from onboard cameras.

Slam B occurs about 45 seconds after the Slam A. Again, it begins with a larger than average wave crest of 4 m followed by a 2 m trough, and a second slightly larger crest. Unfortunately, at this point the data acquisition program lost its signal and data was briefly lost but the on board cameras were able to visually fill in this data gap. Figure 19 shows this sequence of events. The ship encounters the first crest, which comes close to hitting the bottom of the wet deck but is not large enough to cause a slam. The following trough, like the first slam, causes the bow to lift out of the water and pitch up at almost 4 degrees and the second crest is large enough to slam into the bottom of the hull causing the bow to pitch down and an increase in vertical acceleration to almost 0.4 g.

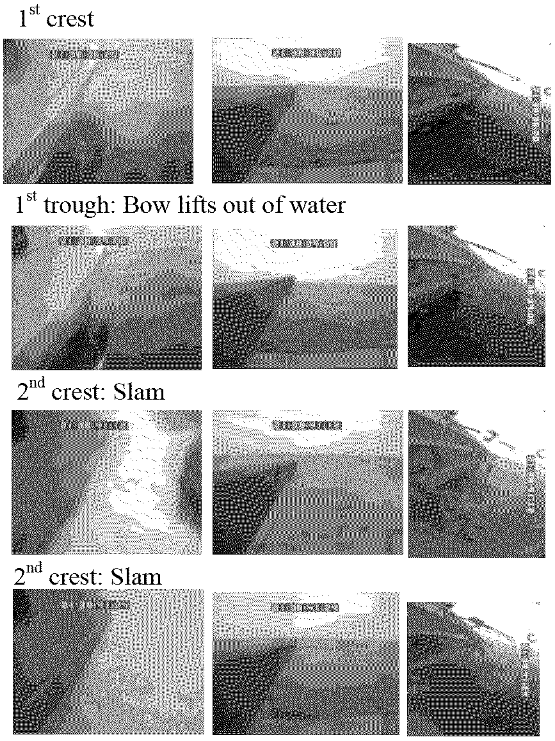


Figure 19: Slam Event 3B: Snapshots from onboard cameras.

The final slam is very similar to the first two. It also begins with a larger than average crest followed a trough that causes the bow to lift out of the water. The actual slam occurs as the ship encounters the second, and larger crest, which slams into the bottom of the hull in the center tunnel. Figure 20 shows this sequence of events.

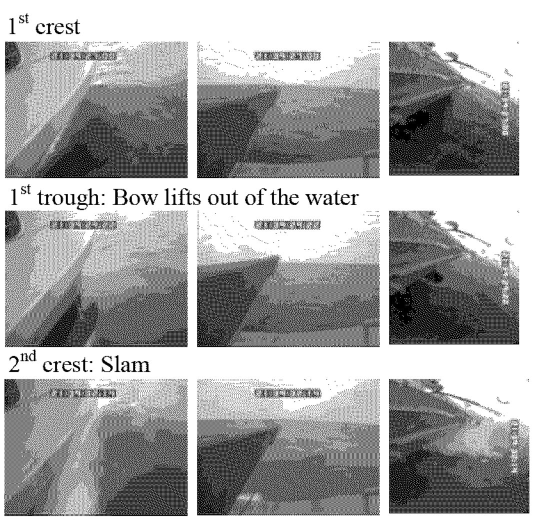


Figure 20: Slam Event 3C: Snapshots from onboard cameras.

All three slams in this time period were caused by two consecutive wave crests that were significantly larger than the average wave height seen by the ship in the given time period. The second wave crest was the wave that caused the actual slam impact and it was always larger than the first crest and close to double the height of the average wave height envelope. In addition, during the wave trough between the two large wave crests the bow of the ship always lifted completely out of the water before the second crest slammed into the ship. During each trough in which the bow was out of the water the ship pitched above the 3 degree envelope and with each crest the bow pitched down below 0 degrees. The peaks in vertical acceleration accompanied the larger wave crests and the bow down pitch.

Figure 21 shows the sequence of events at about 21:37:40 GMT. The plot in Figure 17 indicates that this is a possible slam event since there are two consecutive wave crests greater than 3 m which is similar to the trend seen in the three previously discussed slams. In addition, as shown by the images in the second row of Figure 21, the wave trough after the first crest causes the bow of the ship to lift out of the water, also similar to the previous slams. However, the second crest is not large enough to make impact and cause a slam, explaining why no significant spike in vertical acceleration or pitch is seen. This is an example of a wave train that is close to the necessary conditions for a slam, but the wave crests are not large enough to cause ship motions outside of the average envelope.

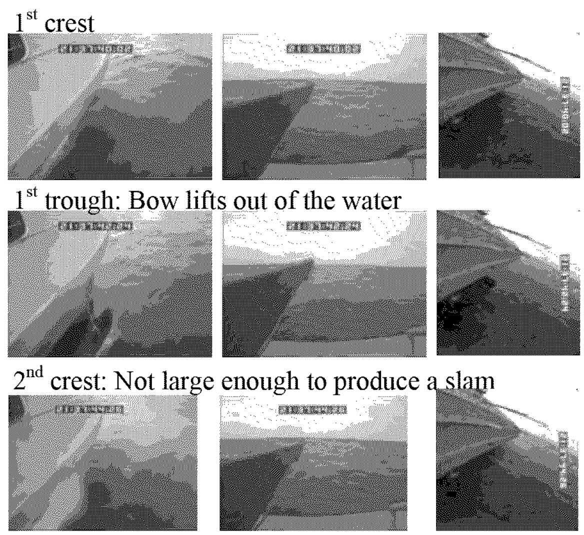


Figure 21: Slam Event 3: Near slam event.

Slam Event 4

Figure 22 provides wave height, pitch, z linear acceleration, and speed plots for Slam Event 4. The spike in the z linear acceleration plot seen at approximately 22:08:45 GMT indicates the slam. Similar to Slam Event 3, Slam Event 4 has wave heights that on average stay within a ±3 m range, pitch angles that stay within a 0 to 3 degree range and vertical accelerations that fluctuate from ±0.2 g's. The event begins with a deep wave trough of about 5 m, followed by a large 6 m crest, another deep trough of 4 m and a large crest of about 4 m before the wave heights start to settle back into the ±3 m envelope.

Figure 23 shows photos from the starboard, bow center, and starboard bowline cameras respectively during the slam event. With the first trough the bow lifts out of the water and with the following crest there is a slam impact. The bow then rises out of the water again with the second trough and the second crest also slams into the bow, this time more violently than the first as seen by the large amount of whitewater the cameras see and the sharp peak in vertical acceleration seen in Figure 22. With each trough the bow of the ship pitches upward, above the 3-degree boundary of the envelope and downward below zero degrees with each crest. The second crest, which causes the more violent slam causes the greatest bow down pitch of -2 degrees that is seen which corresponds with the largest spike in vertical acceleration seen in Figure 22. Figure 24 shows a 30-second section of the plots shown in Figure 22 and illustrates how the ship's greatest bow down pitch corresponds with its maximum vertical acceleration.

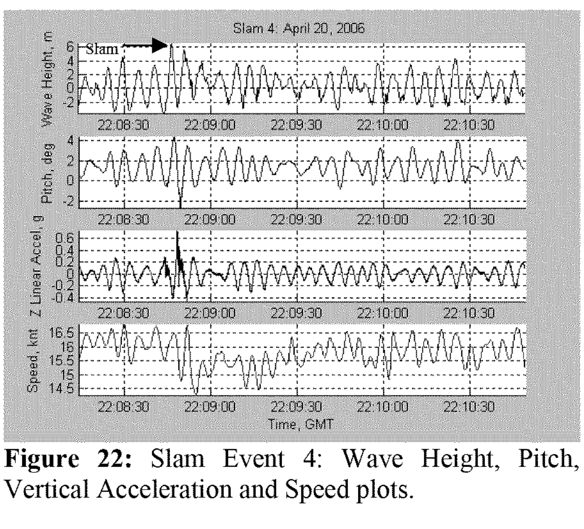
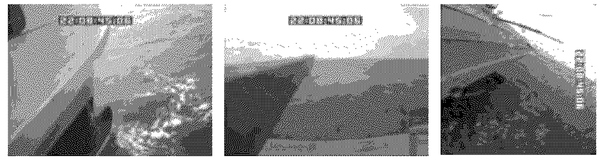
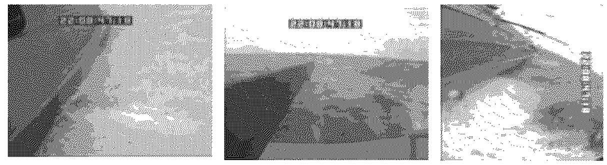


Figure 22: Slam Event 4: Wave Height, Pitch, Vertical Acceleration and Speed plots.

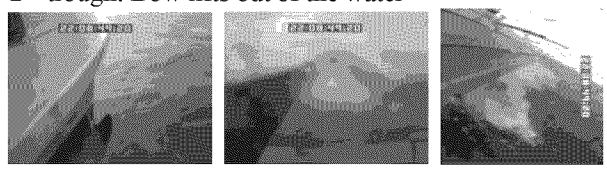
1st trough: Bow lifts out of the water



1st crest: Slam



2nd trough: Bow lifts out of the water



2nd crest: 2nd and more violent slam

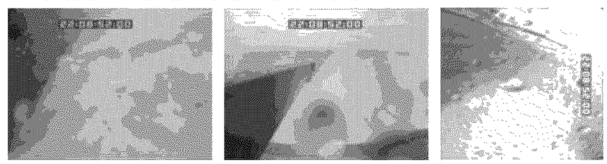


Figure 23: Slam Event 4: Snapshots from onboard cameras.

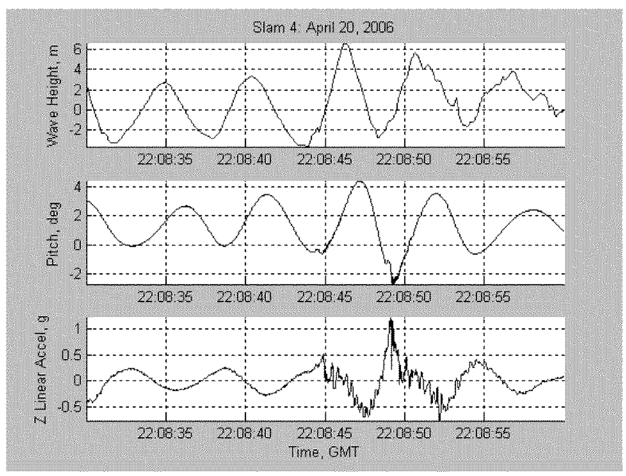


Figure 24: Slam Event 4: 30 second close up of wave height, pitch, and vertical acceleration plots.

CONCLUSIONS

Wave field and ship motions data were collected continuously during a four-day trial from April 18-21, 2006 in the Pacific Northwest. From this data four high-speed slam events were identified and then analyzed. A slam event was defined by the encounter of a wave large enough to make impact with and slam into the bottom of the ship's wetdeck. Slam events were most easily identified in the data by a large spike in the vertical linear acceleration of the ship. Three of the slam events analyzed occurred on the same day while the ship was traveling at 15-20 knots and the other slam event occurred the day before while traveling at a faster speed of 30 knots.

All four slam events had similar characteristics. For the three time periods analyzed on the same day the wave heights seen by the ship stayed within a ±3 m envelope before and after the slam. For the other slam the wave height envelope was ±2 m. In addition, pitch fluctuated within a 0 to 2 or 3 degree range and the vertical acceleration oscillated between ±0.2 g's. The actual slams were caused by waves that were larger than the given envelope and caused ship motions outside of the average range of motion. Each slam involved at least two consecutive wave crests larger than the average envelope and the bow of the ship always lifted out of the water during the trough before the crest that caused the most intense slam. The strength of the slam was determined by the magnitude of the vertical acceleration. The greater the spike in the z linear acceleration above the ±0.2 g envelope the stronger or more violent was the slam. The second large crest always caused a slam, however sometimes both crests had a slam impact. In the case of Slam Event 2 both crests caused a weak slam causing an increase of only 0.2 g above the ±0.2 g envelope to a total vertical acceleration of 0.4 g. Slam Events 1 and 4 also had slams occur with each wave crest however the second crest caused a much more violent slam than the first leading to over an 0.8 g vertical acceleration in both cases.

During each wave trough the bow of the ship pitched upwards, sometimes as high as 4 degrees. The greatest amount of pitch was usually with the trough following the most intense slam. In addition, during each crest the bow pitched downward with the maximum downward pitch angle (-2 degrees) corresponding to the crest that caused the strongest slam. This largest change in pitch that was always seen with the impact of the second slamming wave crest also corresponded with the largest change in vertical linear acceleration. The height of the wave crest that caused the slam impact was often twice the height of the average wave height envelope.

Overall, it can be concluded that for the cases analyzed two consecutive wave crests larger than the average wave height envelope were necessary to cause a slam event. The crest that caused the slam had to be at least 50% larger than the upper bound of the wave height envelope. In addition, it was seen that during the troughs before a slamming crest the bow of the ship lifted out of the water. With each slam impact the ship pitched down below the lower boundary of the pitch envelope and pitched up above the envelope with each crest.